

Vapor Pressure of Hexamethylene Triperoxide Diamine (HMTD) Determined with Secondary Electrospray Ionization Mass Spectrometry

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ABSTRACT

A dynamic method for vapor pressure measurement was developed and used to derive the vapor pressure curve of the peroxide-based explosive hexamethylene triperoxide diamine (HMTD) over the temperature range of 301 – 353°K (28-80°C). The method utilizes a controlled flow of explosive vapor from solid-phase explosive dispersed on an inert solid support and presents it to an ambient-pressure-ionization mass spectrometer equipped with a secondary-electrospray-ionization (SESI) source. The sensitivity of this system enables direct detection of HMTD vapor via an intact molecular ion in real-time at temperatures near 298°K. Direct detection of HMTD vapor at near-ambient temperatures is necessary when characterizing the thermochemical properties of HMTD because its high thermal lability precludes analysis by most conventional vapor pressure measurement methods. The temperature dependence of HMTD vapor was measured using this approach and a Clausius-Clapeyron plot of $\ln(P(\text{Pa}))$ vs. $1/T(\text{°K})$ yielded a straight line with the expression $\ln(P(\text{Pa})) = ((-11245 \pm 440) \cdot 1/T(\text{°K})) + 26.2 \pm 1$ (error limits are the standard error of the regression analysis). From this equation the sublimation enthalpy of HMTD was estimated to be 93.5 ± 3 kJ/mol and the extrapolated vapor pressure at 293.15°K is $\ln(P(\text{Pa})) = -12 \pm 1.8$ or ~52 parts-per-trillion by volume.

INTRODUCTION

Trace chemical detection remains one of several means to screen for the presence of threats and/or contraband and vapor detection plays a key role in the operation of these sensing systems. The majority of deployed chemical detection systems are based on ion mobility spectrometry (IMS) and sample particulate residues on surfaces via a swipe. The surface swipe is then inserted into the detection system where it is flash heated to volatize any condensed phase material that had been collected. The vapor-phase material is then transferred into the ionization region of the IMS where it is ionized and subsequently analyzed. While IMS-based explosives detection involves indirect vapor detection as an intermediate step inside the instrument, there are other methods that employ direct vapor detection in the ambient environment; the most notable of these systems are canines. Thus, given the importance of vapor detection across chemical detection systems it is critically important to understand the physical and chemical processes that underpin these analysis methods, and one of the most critical of these is a compound's vapor pressure. Knowing these vapor source terms help in understanding, testing, and predicting sensor performance. The thermochemical properties of most explosive compounds of importance to the explosives detection community have been characterized, and recently they have been compiled into two comprehensive reviews [1, 2].

One notable omission from these collections of thermochemical data is hexamethylene triperoxide diamine (HMTD). This omission is not due to lack of effort, rather HMTD can be difficult to measure due in part to its instability combined with its ‘very low’ vapor pressure as determined from

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empirical observations. Studies aimed at characterizing the thermal stability of HMTD revealed a kinetic rate constant for decomposition of 10^{-3} sec⁻¹, three orders of magnitude higher than triacetone triperoxide (TATP, 10^{-6} sec⁻¹) with trimethylamine and carbon dioxide observed as the primary HMTD decomposition products at temperatures $<150^{\circ}\text{C}$ [3]. A later study aimed at determining the vapor pressure of HMTD using static headspace sampling and GC-ECD and reported only decomposition products (trimethylamine, N,N'-dimethylformamide, hexamine, and N,N'-methylene bis(formamide)) in the headspace [4]. It is not clear, given the thermal lability of HMTD, if these decomposition products were present in the headspace of the HMTD source material or if they formed as a result of exposure to high temperatures during analysis. From these reports it is clear that the thermal lability of HMTD makes it challenging to directly measure an intact HMTD molecule with conventional instrumental techniques that require elevated temperatures. Alternatives to high temperature methods have also been explored as a way to measure the vapor pressure of peroxide based explosives. A Knudsen effusion technique was successful in measuring the vapor pressure curves of higher vapor pressure peroxides (TATP and diacetone diperoxide (DADP)) but only succeeded in assigning an upper limit on the vapor pressure of HMTD (0.04 Pa) [5]. The authors caution that this value for HMTD is tentative as the mass loss they observed after two months was within the precision of their analytical balance.

As the above studies highlight, thermally unstable compounds with low volatility can be challenging to analyze with conventional analytical instrumentation. While these techniques are highly reliable ‘gold standard’ methods for many important compounds their need to use high temperatures ($200\text{-}300^{\circ}\text{C}$ in the injector and detector and often $50\text{-}200^{\circ}\text{C}$ during transit through the GC column) they are generally not appropriate for thermally labile compounds, e.g. PETN by GC-ECD [6]. More appropriate analysis methods for thermally labile compounds are those which either minimize or eliminate the need for prolonged exposure to elevated temperatures and provide sufficient specificity to distinguish between mass loss due to sublimation and degradation. Recent advancements in ambient-pressure mass spectrometry have offered a more direct, lower temperature approach to detect compounds with a sensitivity that either meets or exceeds those of the more traditional techniques. Recent reports of explosives vapor detection at ambient concentrations in the parts-per-quadrillion range and below in real-time using secondary electrospray ionization (SESI) [7] or atmospheric pressure chemical ionization (APCI) [8, 9] have reignited interest in direct vapor detection of many low volatility chemicals, explosives in particular.

Secondary electrospray ionization (SESI) is one of many atmospheric pressure ionization techniques that enable one to analyze compounds under ambient conditions with a mass spectrometer. SESI was first reported around 1986 in conference proceedings of the American Society of Mass Spectrometry originating from the research group of John Fenn at Yale University [10]. A second report of the technique was detailed in a 1994 paper from the Hill group at the University of Washington [11]. This same group published a second paper using SESI as an atmospheric ionization source coupled to a hybrid ion mobility spectrometer (IMS)-single quadrupole mass spectrometer (MS) for the detection of vapors from illicit drugs [12]. From this point forward the technique began to be viewed as a viable atmospheric pressure ionization source for both IMS and MS.

The technique is straightforward to implement as it involves mixing a gas stream containing a vapor-phase analyte with charged droplets emitted from an electrospray ionization source. The analyte gas stream can be generated either by positive pressure (i.e. by flowing gas through a sample and

directing the output into the MS) or by negative pressure; using a vacuum pump to draw external vapors into the ionization chamber of the MS. Ionization specificity for a particular vapor phase compound can be obtained by the choice of polarity and by tailoring the chemistry of the ESI source with reagents. The value of SESI as an ambient ionization technique stems from the increased sensitivity (and hence detection limits) afforded by the technique relative to other means of vapor detection that involve a preconcentration step. From its initial reports onward, the technique has been shown to be a more efficient way to ionize samples relative to conventional ESI and it is particularly unique in its application to vapors. This improved ionization efficiency has led to several impressive reports detailing the detection of vapors of organic high explosives down to and even below the parts-per-trillion by volume (ppt_v) range in real-time without preconcentration. If preconcentration is used and/or the technique is further augmented with front-end hardware such as ion-funnels [13] or differential mass analyzers [14], detection limits can be further decreased by a factor of 1000, placing the practical vapor detection limits well in to the parts-per-quadrillion by volume range (ppq_v). The types of compounds it has been used to detect have expanded to include organic high explosives [7, 15], fatty acids and urea in breath [16, 17], skin volatiles [18], and organic aerosols [19]. The ability to provide results in near real-time combined with the exceptional detection limits offered by the technique led us to implement this technique for use in this study.

In this work we demonstrate how direct vapor analysis using ambient-ionization mass spectrometry can be extended beyond challenging trace detection problems to yield quantitative thermochemical information from a labile compound (HMTD) that has been difficult to characterize with conventional methods. To facilitate these measurements, we modified a commercial ESI source on a quadrupole time-of-flight (Q-TOF) mass spectrometer enabling direct vapor detection via SESI. We then applied this system to the real-time detection and characterization of vapors comprising the headspace of HMTD at temperatures approaching 25°C. This methodology also enabled us to examine the temperature dependence of HMTD vapor due to sublimation and, by carefully calibrating the system with a surrogate compound, generate a Clausius-Clapeyron plot from which we report for the first time both the sublimation enthalpy and room temperature vapor pressure of HMTD.

EXPERIMENTAL

Reagents and HMTD Synthesis. LC/MS grade methanol, ethanol, water, and formic acid were purchased from VWR (Radnor, PA, USA) and hexamethylenetetramine, hydrogen peroxide (30%), and citric acid were purchased from Sigma-Aldrich (St. Louis, MO). All reagents were used as received. Glass wool and cocaine free-base standard solution (1 mg/ml in acetonitrile) from Cerilliant were purchased from Sigma-Aldrich (St. Louis, MO). HMTD was synthesized according to published methods [20]. *CAUTION: HMTD is an explosive material that is shock and heat sensitive. Use extreme care when working with explosive materials and seek out accepted best practices for handling guidance.* Approximately 672 mg (4.8 mmol) of hexamethylenetetramine was dissolved in 2.175 grams (19.2 mmol) of 30% hydrogen peroxide solution which was stirred magnetically in a beaker standing in a mixture of ice, water and sodium chloride. To the solution one gram (4.8 mmol) of powdered citric acid was added slowly in small portions while the stirring was continued and the temperature of the mixture was kept at 0°C or below. After all the citric acid had dissolved, the mixture was stirred for at least eight hours longer while the temperature was kept at 0°C. The mixture was allowed to warm to ambient temperature as the ice melted. The mixture was then allowed to stand for two hours at room temperature. Afterwards, the white crystalline product was filtered, washed thoroughly with ice water, and rinsed with

cold ethanol. The product was then vacuum dried to ensure that all the solvent had been removed. Once the product had dried it was divided into ~100 mg aliquots and transferred to a refrigerator for storage at 4°C.

Instruments and Ionization Source. All vapor measurements were performed on an Agilent 6520 quadrupole time-of-flight mass spectrometer (Agilent technologies, Santa Clara, CA, USA) equipped with an electrospray ionization (ESI) source and Agilent MassHunter[©] workstation software version B.0.5.00. The manufacturer's ionization source was modified to enable direct vapor measurements using secondary electrospray ionization (SESI) by removing the glass window from the view port and replacing it with an aluminum disk of equal diameter. The disk had a bulkhead fitting through which ¼ inch stainless steel tubing was passed through. The end of the stainless steel tubing was positioned approximately 1.5 inches away from the primary ESI needle. This configuration ensured that the neutral vapor stream crossed the charged droplet stream emitted from the ESI needle facilitating ionization of the vapor stream. The primary ESI solvent was 70:30 methanol:water with 0.1% formic acid, and was delivered at a flow rate of 5 µl/min using a syringe pump (Pump 11 Plus, Harvard Apparatus, Holliston, MA). The mass spectrometer parameters used for data acquisition were: source gas temperature: 300°C, drying gas flow: 5L/min, nebulizer pressure: 15psi, fragmenter voltage: 100 V, and the inlet capillary voltage: 4000 V.

Vapor Generation and Delivery. Test vapor streams were generated by flowing carrier gas over a solid sample of source material (in this work either cocaine or HMTD) that had been immobilized and dispersed onto a solid support, i.e. a vapor generator [21]. Individual vapor generators for cocaine, HMTD and a blank were constructed by cutting a section of glass tube (3.9 mm i.d.) to ~7 cm in length and packing ~5 cm of glass wool inside the tube. 100 µl of cocaine standard solution (1 mg/ml in acetonitrile) or 100 µl of HMTD stock solution (1 mg/ml in acetonitrile, prepared from synthesized material) was added to the glass wool using a syringe (Hamilton, Reno, NV) such that the entire 5 cm column of glass wool was wetted with the solution. The blank generator was similarly packed with glass wool however only acetonitrile was spiked onto the glass wool. The solvent was allowed to evaporate by passing a stream of dry nitrogen through the tube at a flow rate of 50 sccm. Once the solvent had evaporated, both ends of the tube were packed with additional clean glass wool and sealed. When not in use, all vapor generators were stored in a refrigerator at 4°C.

Test vapors were introduced into the SESI ionization source in a pulsed manner using positive pressure to flow clean dry air (CDA) through a vapor generator. The vapor generator was connected to the CDA carrier gas line using hand-tightened ultra-torr fittings. The CDA carrier gas flow was regulated by a mass flow controller (MKS Instruments, Andover, MA) and a valve was placed in line between the output of the generator and the ionization source to minimize background signals due to vapor diffusion from the generator into the source. The CDA flow rate providing the highest signal to noise ratio was 500 ml/min and this flow rate was used throughout the course of these experiments. Temperature control of the vapor generator was achieved by wrapping the generator and all tubing leading to the ionization source with fiber glass sheathed heating tape. The heating tape was powered by a Variac autotransformer that was regulated by a temperature controller (CN8200, Omega Engineering, Stamford, CT). The precision of this temperature controller is ±0.2% full scale and a thermocouple positioned directly on an exterior surface of the vapor generator provided temperature feedback to the controller.

Analysis Methods. Samples were analyzed by recording mass spectra in full-scan mode (approximately one second/scan) over the course of two minutes. The first 30 seconds of the run comprised the instrument response to the ESI spray (i.e. no vapor) after which the valve was opened, the mass flow controller was switched on and sample vapor was presented to the instrument for one minute. This vapor presentation interval was sufficient for the signal in the mass spectrometer to reach a steady-state level. Following the vapor pulse the carrier gas was turned off at the mass flow controller and the valve was closed. The run finished with a second 30-second period of spray background. All instrument responses to a vapor sample at a specific temperature were acquired in triplicate. Vapor generator temperatures used for cocaine were: $21\pm0.5^{\circ}\text{C}$, $25\pm0.5^{\circ}\text{C}$, $28\pm0.5^{\circ}\text{C}$, $37\pm1^{\circ}\text{C}$, and $45\pm1.5^{\circ}\text{C}$ and those for HMTD were $28\pm0.5^{\circ}\text{C}$, $37\pm1^{\circ}\text{C}$, $45\pm1.5^{\circ}\text{C}$, $60\pm1.5^{\circ}\text{C}$, and $80\pm1.5^{\circ}\text{C}$. The error limits on the experimental temperature values represent the total change in the temperature of the vapor generator over triplicate measurements. The vapor generator was allowed to equilibrate for five minutes after reaching the programmed temperature set point and in between vapor pulses to the mass spectrometer. The instrument responses were processed by extracting the time trace (chromatogram) for the $\text{M}+\text{H}^{+}$ ion of either cocaine (m/z 304) or HMTD (m/z 209) and averaging the signal intensity over the portion of the curve where the response had reached a steady-state.

RESULTS AND DISCUSSION

Mass Spectrum of HMTD Vapor

The headspace of HMTD was initially characterized in the mass spectrometer by presenting a gas sample generated from a vapor generator heated to 80°C . This temperature provided a strong instrument response. A background subtracted positive-polarity mass spectrum of HMTD vapor at this temperature is shown in Figure 1. The $\text{M}+\text{H}^{+}$ ion for HMTD is observed at 209.07637, and this ion is accompanied by HMTD associated fragments at m/z 179.06589, 145.06044, 88.04001, 74.06081, and 60.04526. These fragments correspond to those previously observed in the mass spectrum of HMTD using the DART ionization source [22-24]. The ion at 179.06589 corresponds to a loss of formaldehyde from the $\text{M}+\text{H}^{+}$ ion and m/z 229.04263 is a water+methanol adduct of 179. The ion at m/z 145.0604 is a loss of hydrogen peroxide from m/z 179.0659. The fragments observed in the mass spectrum could arise from thermal decomposition of the source material or from an acid catalyzed decomposition of HMTD in the ionization source due to the presence of formic acid in the spray solvent. In an effort to determine the source of this decomposition the temperature of the HMTD vapor generator was ramped (from $35\text{-}80^{\circ}\text{C}$) and the ratios of the primary fragment intensities (179.06589, 145.06044, and 88.04001) to the HMTD molecular ion were determined. These ratios remained constant over temperature the range $35\text{-}50^{\circ}\text{C}$. This observation supports the idea that fragmentation is occurring in the ionization source and is not due to thermal degradation in the vapor generator. At temperatures higher than 50°C , thermal degradation does begin to take place in the vapor generator and the intensity of m/z 74.06081 and 60.04526 increase. These ions correspond to dimethylformamide and trimethylamine, two breakdown products of HMTD that have been previously reported [3, 4].

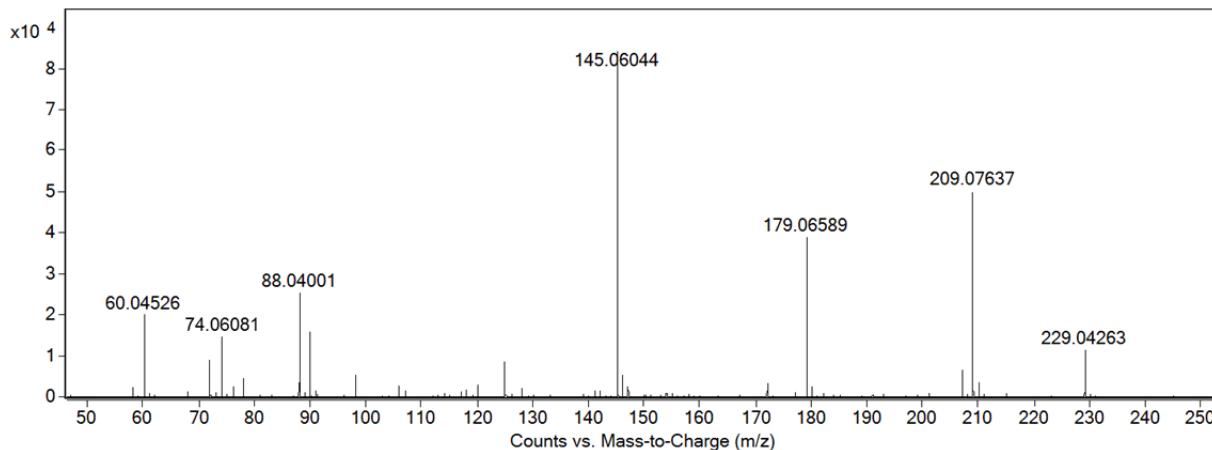


Figure 1 – Background subtracted Q-TOF mass spectrum of HMTD vapor. Vapor generator temperature was 80°C

Calibration of the Instrument Response to HMTD Vapor

The absence of published experimental vapor pressure data for HMTD precluded a direct calibration of the instrument with HMTD vapor. Thus, cocaine vapor was used in place of HMTD vapor in order to calibrate the instrument response. Cocaine was selected for this purpose because its vapor pressure has been measured [25-28] and at 20°C is close to a value calculated for HMTD [29]. A summary of published vapor pressure data for cocaine free base is presented in Table 1.

Table 1 – Published Vapor Pressure Data for Cocaine Free Base

Reference	Temperature Range (°C)	P _{sat} (20°C) 10 ⁻⁷ torr	P _{sat} (20°C) ppt _v	Equation	Coefficients
Lawrence (1984)	21-41	0.88 ± 0.3	116±40	Log ₁₀ P = A - B/T	A = 13±0.5 B = 5884±147
Ziegler (1996)	Not provided	1.2 ± 0.3	157±40	Ln P = slope • (1/T)	Slope = -15293 ΔH _{sub} = 127.2 kJ/mol
Hilpert (1994)	-10-40	6.0	79	Not provided	Not provided
Dindal (2000)	Commercial source	2.96 ± 1.48 (95% confidence)	389±195	Ln (n/V) = A + B • T + error	A = -56.0 B = 0.106 Error = 0.142
	Illicit Source	1.38 ± 0.74 (95% confidence)	181±98	Ln (n/V) = A + B × T + error	A = -70.0 B = 0.152 Error = 0.084

The vapor pressure equation used in this work to calculate the vapor pressure of cocaine was drawn from Lawrence et al. because the full experimental description, results, and the temperature range over which the measurements were made were provided in the report and mirror those used in this work (21-45°C). The other reports listed in Table 1 either omitted critical information (i.e. the temperature range in Ziegler or the model and fit coefficients in Hilpert) or the published values deviated significantly from those previously reported.

In addition to its low vapor pressure, cocaine readily forms an M+1 protonated adduct when ionized at atmospheric pressure (as does HMTD) and its proton affinity is 930.1 kJ/mol as calculated via

ab initio methods [30]. The proton affinity for HMTD has not been published however we estimate it to be in the 947-985 kJ/mol range using published values for the non-peroxide analogues listed in Table 2 [31].

Table 2 – Published Proton Affinities for Non-Peroxide Containing HMTD Analogues

Name	Molecular formula	Proton affinity (kJ/mol)
1,6-diazabicyclo[4.4.4]tetradecane	C ₁₂ H ₂₄ N ₂	947
1,5-diazabicyclo[3.3.3]undecane	C ₉ H ₁₈ N ₂	972
1,4-diazabicyclo[2.2.2]octane	C ₆ H ₁₂ N ₂	985

The estimated proton affinities for both cocaine and HMTD are high relative to gas-phase methanol, the primary protonated charge carrier in the ESI source. Given this significant energy difference, the protonation reactions for both molecules are highly favored thermodynamically and as such any differences in ionization yield (which are important to assess when considering cocaine as a surrogate for HMTD) will arise due primarily to differences in the ionization rate coefficients. In an effort to explore these ionization differences we estimated the ionization rate coefficients using equation 1

$$k_{ADO} = \sqrt{\frac{\pi\alpha q^2}{\mu\epsilon_0}} + \frac{C\mu_D q}{\epsilon_0} \sqrt{\frac{1}{2\pi\mu k_B T}} \quad (1)$$

derived from average dipole orientation (ADO) theory [32, 33]. In equation 1 α is the polarizability of the molecule, q is the elemental charge, μ is the reduced mass (calculated using a methanol dimer as the charging ion in the SESI source), C is the dipole locking constant, μ_D is the dipole moment of the molecule, and T is the temperature in Kelvin. We then used these rate constants to further calculate the probability of ionization for both cocaine and HMTD [10]. The results of this analysis along with the values used as inputs into the calculation are listed in Table 3.

Table 3 – Molecular Parameters Used to Calculate Ionization Rate Coefficients

Compound	Molecular Weight (g/mol)	Ion Mobility (cm ² /V·sec)	Polarizability (Å ³)	Dipole moment (Debye)	Dipole locking constant	Rate constant × 10 ⁹ cm ³ /sec	Probability of ionization (P _i) × 10 ⁴
Cocaine	303	1.15	32.2	2.50	0.125	2.2	10.6
HMTD	208	1.50	17.4	0.68*	0.080	1.5	5.4

*estimated from quantum chemical calculations

We calculated molecular properties that could not be found in the literature using quantum chemical methods (B3LYP/6-31G(d,p) level of theory) as values computed using these parameters have shown good correlation between theory and experiment [34]. The net result of this calculation indicates that cocaine has a probability of ionization that is about a factor of two greater than HMTD, therefore the intensity values measured for HMTD on the mass spectrometer were adjusted for this difference. Additionally, cocaine decomposes into methyl ecgonine (among other compounds) at increased

temperatures and when presented to our SESI ionization source [35]. Importantly, the fraction of cocaine molecules detected as the cocaine $M+H^+$ ion range from 0.20 – 0.40 across the experimental temperatures in our system and is very close to 0.25 – 0.31 range observed for HMTD. Thus, after correcting for the difference in the probability of ionization, the instrument response factor for the $M+H^+$ ion of cocaine vapor is expected to be close to that for HMTD. This means that for every vapor molecule of cocaine presented to the ionization source and detected under a fixed set of instrumental conditions we can assume, with reasonable confidence, that the instrument response will be similar to an equal number of vapor-phase HMTD molecules.

This assumption enables us to calibrate the instrument's response to cocaine vapor, or more precisely the number of molecules delivered to the instrument as a function of the vapor pressure of cocaine at a particular temperature, and then use the equation derived from this relationship to quantify an unknown instrument response to HMTD vapor at a particular temperature. A plot of the instrument response to varying concentrations of cocaine vapor, generated by changing the temperature on the source material, is shown in Figure 2. The vapor pressure values plotted on the x-axis were calculated using the experimental temperature as an input into the vapor pressure equation published in Lawrence. The correlation between the instrument response and the calculated vapor pressure of cocaine at a given temperature returned an R^2 value of 0.9994.

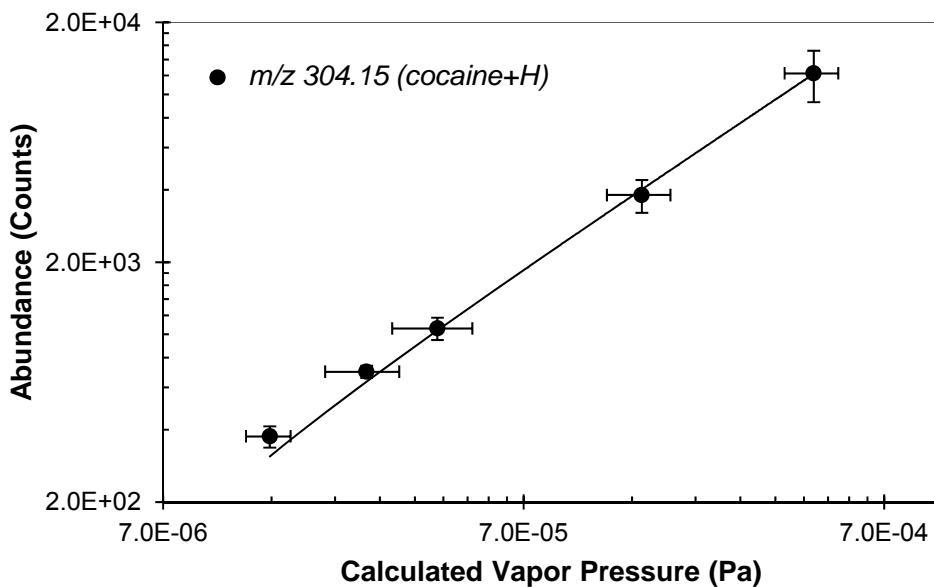


Figure 2 – SESI/Q-TOF calibration curve for cocaine vapor as a function of vapor pressure. Vapor pressure values were calculated using the coefficients and equation published in Lawrence [25].

The same instrumental setup was then used to characterize the instrument response to HMTD vapor as a function of temperature. The cocaine vapor generator was replaced with one containing HMTD and triplicate measurements were made on the MS at five temperature points over the range of 28–80°C. The response of the instrument to HMTD vapor was recorded by monitoring the intensity of the HMTD molecular ion at m/z 209.0766 and correcting this value for the difference in ionization probability. The equation derived from the cocaine calibration curve in Figure 2 was used to convert the

measured intensity of the HMTD molecular ion into a vapor pressure. These data were then compiled into Clausius-Clapeyron plot by plotting the inverse temperature (in °K) vs. the natural logarithm of the HMTD vapor pressure and a linear relationship was observed. This plot, together with the fit derived from the Clausius-Clapeyron equation is shown in Figure 3. The y-axis error bars shown in the plot are the combined error from the calibration curve and the instrument variance over triplicate analyses. The x-axis error bars reflect the change in temperature of the vapor source over the course of the triplicate measurements. The red line in Figure 3 is a curve derived from Antoine coefficients published as a result of a computational modelling effort and is shown for comparison to the experimental data [29]. It is important to note that the coefficients listed in [29] are reported to return a log base 10 of the vapor pressure however when we evaluated this expression using the published coefficients we concluded that the equation was actually returning the natural log of the vapor pressure. To check that these coefficients were indeed returning base e values we compared the calculated values at 25°C to values published in [2] for two well characterized explosives, TNT and PETN. The published vapor pressure values were returned when the natural logarithm was used in the final stage of the calculation. Thus, when we compare our experimental data to the base e vapor pressure curve for HMTD derived from [29] we see good correlation between the two. Furthermore, the fact that we see a linear relationship for the experimental data in Figure 3 supports the notion that we are detecting HMTD in the vapor phase as opposed to particles of HMTD.

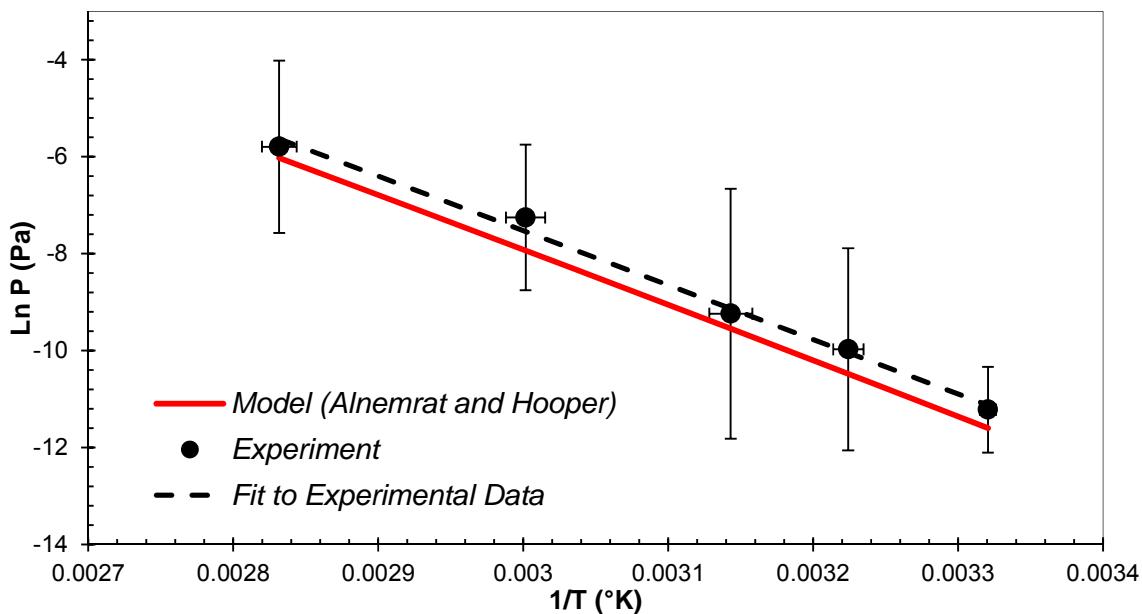


Figure 3 – Clausius-Clapeyron plot for HMTD. Closed circles are the experimental data points, solid black line is a least squares fit to the experimental data, and the solid red line is a modelled HMTD vapor pressure curve derived from [29]. See text for an explanation of error bars.

From the slope of the line fit to our experimental data we determined the enthalpy of sublimation (ΔH_{sub}) for HMTD to be -93.5 ± 3 kJ/mol. Using this expression we extrapolate a vapor pressure at 20°C to be 5.3×10^{-6} Pa or 52 ppt_v. A summary of our results for HMTD together with the model and coefficients is provided in Table 4.

Table 4 – Summary of Experimental Results for HMTD

Model	$\ln P = -\Delta H_{\text{sub}}/R \cdot (1/T) + c$ Where: P = Pascal T = °K R = 8.314
Coefficients	$\Delta H_{\text{sub}} = 93.5 \pm 3 \text{ kJ/mol}$ $c = 26.2 \pm 1$
Number of data points	15
Correlation Coefficient	0.9929

The HTMD vapor pressure value at 20°C calculated from our experimental data is within 40% of the value reported by [29]. A short summary of values derived from our analysis compared to the model are provided in Table 5.

Table 5 – Comparison of Experimental and Model Vapor Pressure Data for HMTD

	ΔH_{sub} (kJ/mol)	P_{sat} (20°C) Pa	P_{sat} (20°C) ppt_v
Experiment	-93.5	5.3×10^{-6}	52
Model [29]	-95	3.3×10^{-6}	33

Considering the results obtained here together with other published studies aimed at characterizing the headspace composition of HMTD it is apparent that this compound presents a dynamic headspace profile, particularly within the context of thermal desorption. The enthalpy of sublimation obtained as a result of this work (-93.5 kJ/mol) is close to the activation energy of decomposition (-120 kJ/mol) reported in [4]. The fact that these two values differ by ~27 kJ/mol of energy indicate that both sublimation and thermal decomposition will likely contribute to the headspace profile at temperatures only slightly above ambient. This interplay between the vaporization of condensed phase material and decomposition has been observed in other explosive compounds as well, namely 1,3,5-Trinitroperhydro-1,3,5-triazine (RDX) [36] and 5-nitro-2,4-dihydro-3H-1,2,4-triazol-3-one (NTO) [37], however the energy difference between these two processes (~ factor of 2 in the published reports) is greater than what is observed here for HMTD.

CONCLUSIONS

An ambient ionization mass spectrometry method was developed that facilitates direct real-time measurement of HMTD vapor via sublimation from condensed phase material. The system utilizes a secondary electrospray ionization (SESI) source coupled to Q-TOF mass spectrometer. Test vapors are generated from a temperature controlled vapor generator delivered to the ionization source. The HMTD

vapor mass spectrum in positive mode consisted of a molecular ion formed via proton attachment as well as HMTD associated fragments. The instrument response to HMTD vapor was calibrated by using cocaine vapor as a surrogate for HMTD as the instrument response function is similar for cocaine. This system was then used to characterize the temperature dependence of HMTD vapor and fit to the Clausius-Clapeyron equation. From this fit an enthalpy of sublimation of 93.5 ± 3 kJ/mol was determined and a vapor pressure at 20°C was extrapolated to be 5.3×10^{-6} Pa. This measurement represents the first published value of the heat of sublimation and vapor pressure for HMTD. The values obtained as a result of this experimental work correlate well with those determined via modelling. The combined high sensitivity and rapid response time of the SESI-MS system opens up interesting possibilities for real-time detection of HMTD using its vapor signature including transient plume detection and characterization.

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